OPTIMISING THE PATTERN OF SEMI-RIGID COLUMNS TO IMPROVE PERFORMANCE OF RAIL TRACKS OVERLYING SOFT SOIL FORMATION

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ABSTRACT

With Australia facing a rapid increase in population in the next 30 years, the government is being proactive in handling the forecasted growth. The release of 2010 Metropolitan Transport Plan by the New South Wales (NSW) Government shows that the State of NSW will see an increase in commuter travel by rail. The NSW rail system is one of the most complex networks in the world and due to population growth, the network will require further expansion with construction of new railway lines partly on weak and marginal ground and will also require more frequent train running on existing lines. This study seeks to identify the effectiveness of semi-rigid inclusion ground improvement techniques particularly stone columns and deep soil mixing in controlling settlement of soft soils when placed under the dead loads of the rail structure and the large live loads of freight trains. The employed numerical study assesses the relationship between the column position in the track cross section and the overall settlement of the ballasted rail formation. The numerical results show that the overall settlement of the track reduces significantly with the use of columns close to the centre of the track and not just under the rail. In addition, application of one layer of geogrids between sub-ballast and sub-grade assists to reduce the maximum settlement of track decreasing the future maintenance costs.

1 INTRODUCTION

Australian railway has recently seen an increase in major periodic maintenance works and the development of new rail lines to integrate into the existing rail network through reconstruction of redundant rail lines and construction of new tracks. According to Sydney Rail Performance Data (2011), the increasing traffic congestion has shifted people from self private transportation to public transportation, such as trains and buses. With a daily average of 104,455 and 80,120 during the morning and afternoon peak hour, Sydney metropolitan railway system has certainly achieved one of the busiest rail transportation in the world. By 2036, Sydney is expected to grow by 1.7 million to a population of 6 million. On an average weekday in 2036, there will be over 2 million rail trips, up from 850,000 in 2006. Due to this forecasted increase, the NSW government is heavily investing funds into rail as well as other transport modes to ensure future transport systems can accommodate the growth in the population. Therefore, a need to maintain a competitive edge over other means of transportation has increased the pressure on the railway industry to improve its efficiency and decrease maintenance and infrastructure costs. In the case of ballasted railway tracks, the cost of substructure maintenance can be significantly reduced if a better understanding is obtained of the physical and mechanical characteristics of the rail substructure and, more importantly, by effectively reconstructing and constructing rail tracks to enhance the existing standards and design criteria, which will ensure minimum maintenance expenditure.

Continual urban development and expansion is leading to an ever increasing demand on existing rail infrastructure. As our existing infrastructure reaches its maximum capacity, it is essential to upgrade existing, or construct entirely new infrastructure to service the needs of the population. In many parts of the globe urban development has reached the point where there is no longer any suitable land on which readily to construct infrastructure using the conventional methods. As a result, structures are being constructed on weak or problematic soils, which can not only fail due to an inability to sustain the loads of the supported structure but also experience large differential and total settlements. Differential settlement can result in unexpected increase in the stresses in the supported infrastructure above that which it has been designed to sustain. These settlements also increase the need for maintenance to provide usable rail infrastructure. To address this problem, there has been significant investigation in the area of geotechnical engineering, into methods for improving the bearing capacity and controlling the settlement of the problematic formations. These investigations have lead to the development of numerous ground improvement techniques such as: Dynamic Compaction, Jet Grouting, Deep Soil Mixing, Dynamic Replacement, Vacuum Consolidation and Stone Columns. There are a number of factors, which dictate the most suitable ground improvement technique; these range from the significance of the structure, the anticipated service life, construction loadings, and the consequences of failure, to the sub-surface soil conditions. In this paper, after a brief review of ballasted railtrack problems and improvement techniques, numerical analysis is employed to find the optimum pattern and number of semi-rigid inclusion columns, namely deep soil mixing and stone columns, to improve the rail track performance on soft soils.

2 RAIL TRACK FORMATION IMPROVEMENT

Formation plays a vital role in providing sound track geometry and stability. Weak soils must be dealt with according to standards. Weak sub-grade can cause drastic track settlement as the formation strength will not be sufficient to carry the cyclic loading imposed by trains. If formation is built up of soft or marginal soils, it can become unstable either in a progressive manner or all of a sudden occasion. Swift failure is however rare and usually occurs by either a drastic change in climate including heavy rain or flooding or if there is a notable increase in wheel loads. Progressive shear failure however, is more likely to occur, which leads to rapid track geometry degradation when exposed to speed and axle loads by rolling stock traffic.

2.1 PROBLEMS ASSOCIATED WITH BALLASTED RAIL TRACKS

Ballast breaks down and deteriorates progressively under heavy trainloads, settles differentially due to weak subgrade and poor drainage, fouls due to clay pumping and ballast breakage, and rail track buckles due to lack of confining pressure (Figures 1-6).

Figure 1: Track fouls due to clay pumping (Selig and Waters, 1994)

Figure 2: Track fouls due to ballast degradation

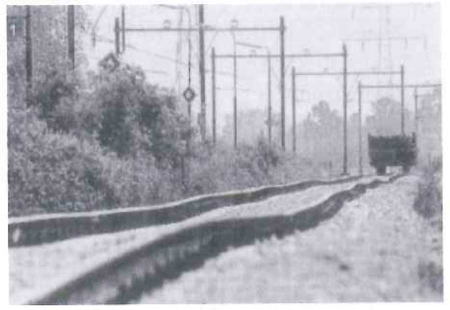

Figure 3: Track settles differentially due to weak subgrade (Suiker, 2002)

The problems, associated with track foundation, result in costly rail track maintenance including ballast cleaning and replacement (Indraratna *et al*., 2011). Hence, an accurate quantification of mechanical behaviour of ballast, particularly at presence of under-lying soft soil formation is essential for stabilisation measures of railway tracks. On the other hand, the cost of substructure maintenance can be significantly reduced if a better understanding of the rail substructure behaviour is obtained.

Figure 4: Soft soil formation and track poor drainage

Figure 5: Clay pumping and void clogging

Figure 6: Bulli track in NSW indicating ballast degradation before maintenace

2.2 VARIOUS APPROACHES FOR TRACK FORMATION STABILISATION

2.2.1 Inclusion of Geosynthetics

A wide range of geosynthetics with different properties have been developed to meet highly specific requirements corresponding to various uses in new rail tracks and track rehabilitation for more than three decades. Enhancing the performance of rail tracks by composite geosynthetics is now extensively considered by rail industry. Based on relatively low cost and the proven performance of geosynthetics in a number of railway applications, many researchers (e.g. Raymond, 1994; Indraratna *et al.*, 2011; Lieberenz. and Weisemann, 2002; Indraratna and Khabbaz, 2008) have conducted experimental programs, field study and numerical analysis to investigate the effects of the different types of geosynthetics on ballast degradation and fouling, track settlement and stabilisation of railway formation. Geotextiles are widely used as a strengthening and separation materials. They are placed between subgrade and subballast. However geotextiles have been found not to be very effective in stopping mud pumping, as the formation fines are too small and

can still penetrate the geotextiles. It can be noted that geotextiles can reduce the height of subballast if they are used together with a sand layer (Fatahi *et al*.., 2011). In addition, according to Fatahi and Khabbaz (2011), the ballasted track using blended ballast with geogrids, placed between sub-ballast and subgrade, can achieve its optimum performance, which has even less settlement than the fresh ballast without geogrids.

It was expected that the use of geosynthetics would encourage the reuse of discarded ballast from stockpiles, reducing the need for further quarrying and getting rid of the unsightly spoil tips often occupying valuable land in the metropolitan areas. The fundamental and experimental studies (e.g. Indraratna *et al*., 2006) proved that geogrids bonded with a drainage fabric (geotextiles) will increase the load bearing capacity of the ballast bed while minimising the lateral movement of ballast and reducing degradation. Use of the composite geosynthetics also prevents the occurrence of liquefied soil (slurry) and its upwards pumping that would foul the ballast.

2.2.2 Vertical Drains

Low-lying areas with high volumes of plastic clays can sustain high excess pore water pressures during both static and cyclic loading. The effectiveness of prefabricated vertical drains (PVDs) for dissipating pore water pressures and factors influencing its efficiency (e.g. smear effect) was investigated by researchers (e.g. Indraratna *et al*., 2011). In poorly drained situations, the increase in pore pressures decreases the effective load bearing capacity of the formation. Even if the rail tracks are well built structurally, undrained formation failures can adversely influence the train speed apart from the inevitable operational delays.

Under railway tracks, where the significant amount of the applied load is typically sustained within the several meters of the soil surface, sufficient ballast and subballast depths are provided. In this regard, relatively short prefabricated vertical drains may be adequate in design. Short PVDs (4-8 m) can dissipate the cyclic pore pressures, curtail the lateral movements and increase the shear strength and bearing capacity of the soft formation to a reasonable depth below the subballast. In other words, this will provide a "stiffened" section of the soft clay up to several meters in depth, supporting the rail track within the predominant influence zone of vertical stress distribution. If excessive initial settlement of deep estuarine deposits cannot be tolerated in terms of maintenance practices, the rate of settlement can still be controlled by optimising the drain spacing and the drain installation pattern. In this way, while the settlements are acceptable, the reduction in lateral strains and gain in shear strength of the soil beneath the track, improve its stability significantly. Indraratna *et al.* (2011) showed that PVDs can effectively speed up the excess pore pressure dissipation and limit the lateral displacement induced by the cyclic loads.

2.2.3 Vegetation or Tree Roots

Tree roots can be an effective form of natural soil reinforcement apart from dissipating the excess pore water pressure, and generate sufficient matric suction to increase the shear strength of the surrounding soil. In Australia, various forms of native vegetation grow along rail corridors. Tree roots provide three independent stabilising functions: (a) reinforcement of the soil, (b) dissipation of excess pore pressure and (c) establishing matric suction increasing the soil shear strength. The matric suction established in the root zone propagates radially and contributes to ground stabilisation near the root zone. Using native vegetation in semi-arid climates and coastal regions of Australia has become increasingly popular for stabilising railway corridors built over expansive clays and compressive soft soils. As a consequence of passage of heavy trains or ballast tamping to reshape and level the ballast, a ballast bowl (or ballast pocket) in which water accumulates and softens the ground can be formed under the track granular layer. In order to quantify pore pressure dissipation and induced matric suction generated by transpiration, Fatahi *et al*., (2007) carried out a finite element analysis using ABAQUS software. More details about the model can be found in Fatahi *et al.* (2007). This type of formation improvement highly depends on type of soil, trees and climate.

2.2.4 Physical and Chemical Stabilisation

Several remedial measures are available to strengthen subgrade materials. The common hydraulic binding agent is lime in particular for stabilisation of soft clay formation. Using lime can substantially increase the stability and load-bearing capacity and decease permeability of the subgrade. Other chemical agents are cement, fly ash, mixture of fly ash-cement or lime, lignin (a by product of paper manufacturing containing wood sugar and lignosulfonate), blast furnace slag-modified grouts and bitumen. Optimising the percentages of applied chemical agent to soil and the ratio of water to agent are essential for a successful stabilisation. Other key aspects in employing pozzolanic stabilisers are the type of the reactive soil, mix design protocol and construction practices. The sulphate content of the soil, or more importantly the lack of sulphates, is critical. The presence of excess sulphate in formation results in unacceptable heave.

One of the physical stabilisation methods of weak soils is stone column construction, which involves the partial replacement of weak soil with compacted vertical columns of stone, behaving as *in situ* reinforcement of soft soil. The advantages of this method are: increased bearing capacity, reduced settlement, accelerated consolidation, improved slope stability and liquefaction control. The presence of stone columns would transform the ground into a composite mass of granular cylinders. The composite ground can have a lower compressibility and a higher shear strength in comparison to natural soft soil.

During the past 25 years several railroad companies and the asphalt paving industry have developed optimum or recommended designs and applications for using a layer of hot-mix asphalt within the track structure in lieu of conventional granular subballast. The hot-mix asphalt is designed similar to the bottom layer of perpetual highway pavement. It is designed to be a medium modulus, flexible, low voids, fatigue resistant layer that will accommodate high tensile strains without cracking. The results of the testing program conducted by Rose *et al.* (2008) showed that the asphalt binders and hot-mix asphalt do not exhibit any indication of excessive hardening, brittleness, weathering, deterioration or reduction in fatigue life after many years in the insulated track-bed environment.

3 NUMERICAL MODELLING

In this study, to investigate the influence of columns pattern and spacing in conjunction with geosynthetics on deformation of track due to the trainload, finite element modelling using PLAXIS ver. 9 (2008) is employed. The model geometry is established considering a typical ballasted track cross-section with concrete sleepers as recommended on the NSW rail network with depth of each layer from top to bottom including rail, sleeper, ballast, and sub-ballast are 0.1 m, 0.15 m, 0.3 m and 0.15 m, respectively. The subgrade depth is assumed to be 10 m to examine the rail track performance. The gauge length of the track is 1.4 m. Figure 7 illustrates the cross section of the rail employed in the finite element model. The track section is modeled using 15 node plane-strain triangular elements and because of symmetry only one half of the cross-section is modeled. Initial stresses before construction of the track were generated using k_0 procedure balancing horizontal and vertical stresses with the *in situ* stresses due to gravity. The simulation was conducted using the Plastic Analysis Method in PLAXIS. Standard fixities are selected to create the boundary conditions, where the roller boundary conditions are generated at the vertical sides and the pin fixities at the base. The water table is at the surface of the ground just below the sub-ballast layer. The train load is 125 kN/m considering as a typical axle train load of 25 tonne/axle.

This simulation is conducted for two configurations: (i) without geogrid reinforcement and (ii) with geogrid reinforcement. Two layers of geogrids are placed at the interface between the subgrade and sub-ballast, and sub-ballast and ballast. Basal reinforcement (Tencate with the tensile strength of 600 kN/m) with an initial input stiffness, EA of 6000 kN/m for 10% strain is adopted to simulate the geogrids. It can be noted that E denotes the Young's modulus and A is the cross sectional area. Interface elements simulating the interaction between the geogrids, and sub-ballast and sub-grade with the strength reduction factor of 0.75 have been included. The stiffness matrix for quadrilateral interface elements is obtained by means of Gaussian integration using the integration points.

Due to the plane strain assumption that the cross-section is uniform over an infinite length, modification of the sleeper properties is required to accurately simulate the cross-section's behaviour under load. Sleepers are typically 200mm in width and 600 mm centre to centre and ballast fills the spaces between individual sleepers. So a combination of concrete sleepers and ballast properties needs to be used to approximate the behaviour of this composite layer over an infinite length. To establish the appropriate material properties, a weighted average of both material properties is taken over one unit length of the composite material (being 600 mm), see Figure 8.

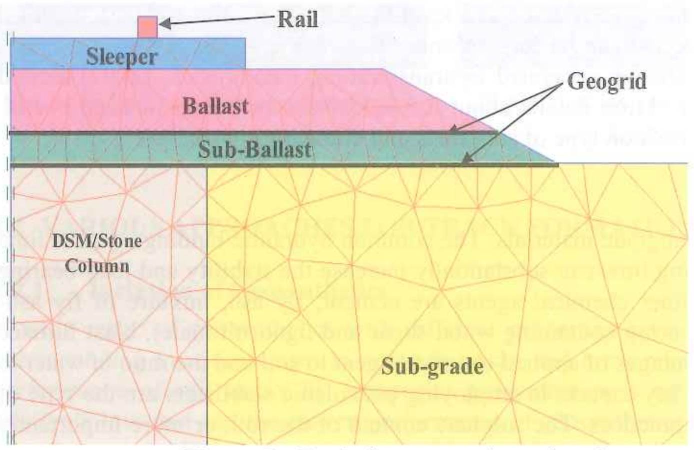

Figure 7: Typical cross-section of track

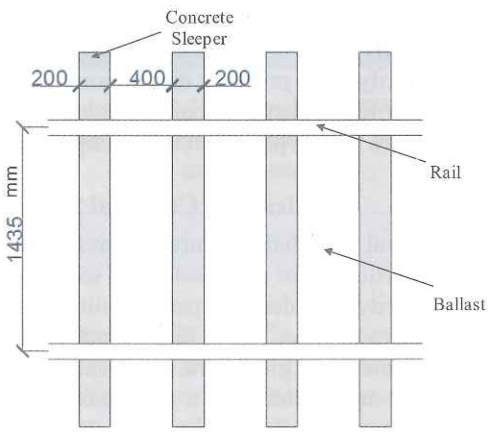

Figure 8: Unit length between sleepers (plan view)

Conservatively, the sleeper spacing is taken into account for two dimensional plane-strain analysis using the equivalent material properties. The material properties used have been selected according to the NSW State Rail Authority, Australia, and published literature. Hardening soil model (HSM), is adopted as the constitutive model for ballast and

sub-ballast. The yield surface of the hardening plasticity model expands due to plastic straining. Both shear hardening (to model irreversible strains due to primary deviatoric loading) and compression hardening (to model irreversible plastic strains due to primary compression in oedometer loading and isotropic loading) are considered. In addition, Mohr-Columb (MC) elastic-perfectly plastic model is adopted for sub-ballast and sub-grade. Table 1 summaries the material properties for various sections of rail track used for the finite element simulation in this study.

Table 1: Material Properties for Rail Track Simulation

Parameter	Ballast [1]	Sub-ballast [1]	Sub-grade [2]	Sleeper [3]	Rail [4]
Material Model	HSM	MC	MC	Elastic	Elastic
γ_{sat} :(kN/m^3) (unit weight)	16.3	22.3	21	24	78
E_{50}^{ref} (MPa) (secant stiffness)	150	-	-	-	-
E_{oed}^{ref} (MPa) (tangent stiffness)	150	-	-	-	-
E_{ur}^{ref} (MPa) (unloading stiffness)	450	-	-	-	-
E: (MPa) (Young's modulus)	-	100	2.62	10000	200000
ν (poisson's ratio)	0.2	0.35	0.25	0.3	0.15
c: kPa (cohesion)	0	0	17.5	-	-
φ: degree (friction angle)	50	45	0	-	-
p_{ref}: (kPa) (reference stress)	100	-	-	-	-
m (model constant)	0.5	-	-	-	-
K_0^{nc} (K_0 for NC soil)	0.3	-	-	-	-
R_f (failure ratio)	0.9	-	-	-	-

[1] After Indraratna et al. (2007); [2] Soft clay; [3] Typical reinforced concrete; [4] Typical steel

Elastic-perfectly plastic material model considering Mohr Columb failure criterion has been adopted for deep soil mixing (dry) and stone columns materials. Design parameters are presented in Table 2.

Table 2: Properties for Deep Soil Mixing and Stone Columns

Parameter	Stone Column [1]	Deep Soil Mixing [2]
γ_{sat} :(kN/m^3) (saturated unit weight)	20	20
E: (MPa) (Young's modulus)	72.5	13
φ: degree (friction angle)	38	0
c: kPa (cohesion)	0	100
ψ: degree (dilation angle)	24	0

[1] Data taken from Fatahi *et al.* (2012), [2] Typical values for dry soil mixing

It should be noted that the sub-grade was modelled using undrained properties of the soil. Deep soil mixing and stone columns similar to the concrete sleeper suffer from the limitations of the 2D plane strain modelling in PLAXIS-2D. To account for this, a weighted average of properties has been adopted considering the area of the sub-grade material and the area of the stone column for unit length perpendicular to the modelling plane. The spacing between each row of columns along rail track has been chosen as 1.5 m for this modelling with the diameter of each column being 1 m. As mentioned earlier, in this study the influence of columns pattern particularly number of columns in the track cross section and their spacing, on the performance of the track is investigated. Figure 9 illustrates the two selected patterns of columns used in this study. Authors try to compare effectiveness of construction of two and three improved columns in the cross section with various offset distances from the track centreline.

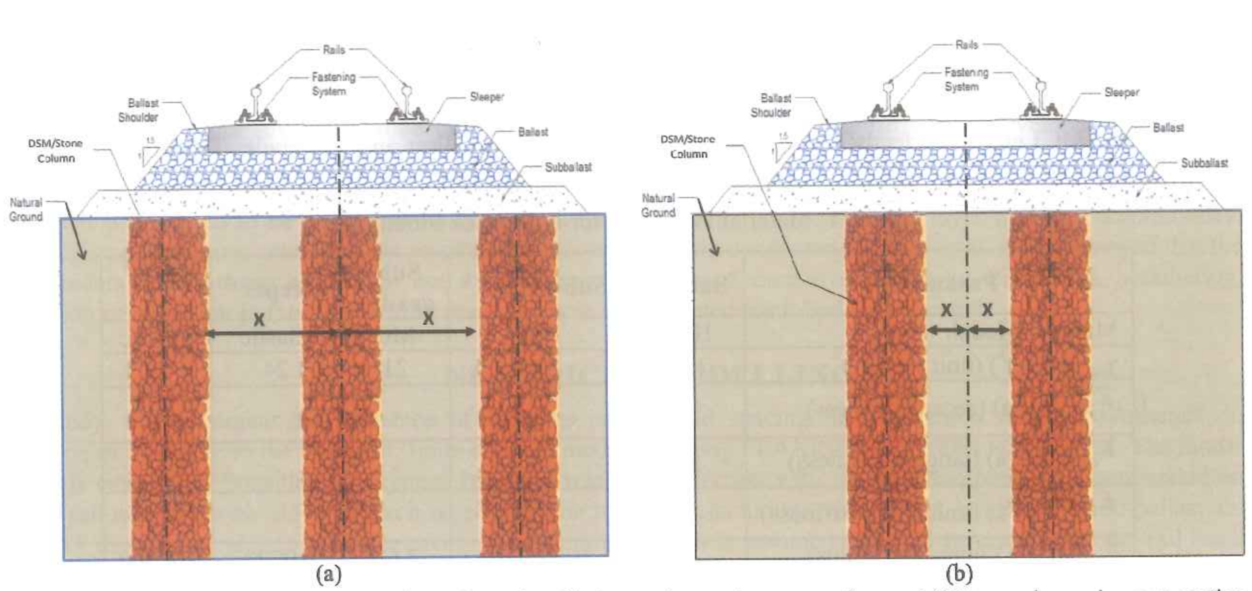

Figure 9 – Column pattern to improve railway formation (a) three columns in cross section, and (b) two columns in cross section

4 RESULTS AND DISCUSSION

Figure 10 shows contours of the horizontal deformations induced by the train load for the natural ground. As expected, the subgrade is more confined right below the sleeper resulting in less lateral deformation. As indicated in Figure 10, directly under the sleeper, there is minor horizontal displacement and outside this confined zone, the subgrade experiences horizontal displacements. The maximum horizontal displacement, occurring directly under the sleeper edge, is 135 mm. According to Figure 11, by introducing two overlapping stone columns in the centre of the track cross section (x=0.5m), the maximum horizontal deformation of the ground below the sleeper edge reduces to 19 mm (86% reduction in the maximum horizontal displacement). The maximum horizontal displacement occurs on the interface of the columns and the *in situ* soil approximately 1.2 m below the ground surface as shown in Figure 11.

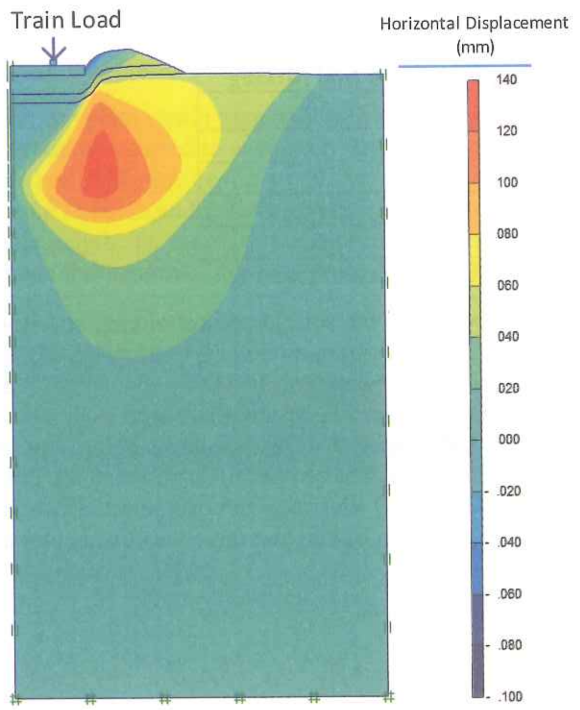

Figure 10: Contours of horizontal displacement under train loading for natural ground

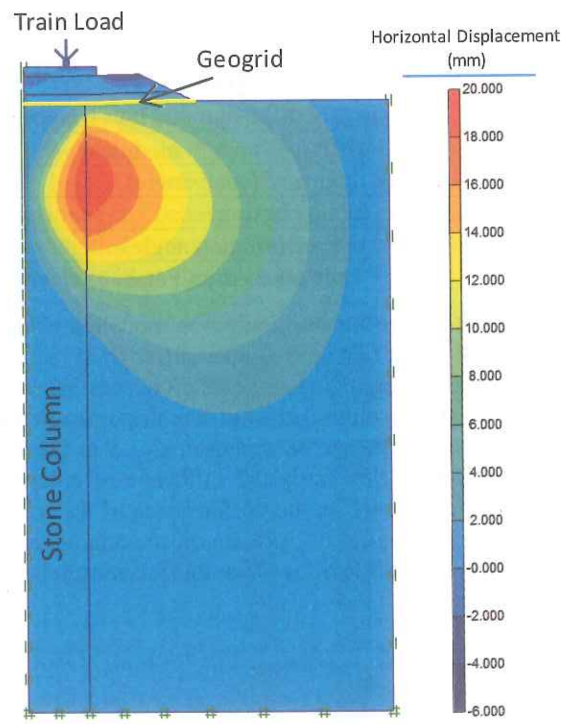

Figure 11: Contours of horizontal displacement under train loading for the ground improved using two stone columns offset 500 mm from centre with one layer geogrid

Figures 12 and 13 indicate the contours of the horizontal displacements when the sub-grade is improved using two and three stone columns offset 1.4 m from the track centreline, respectively.

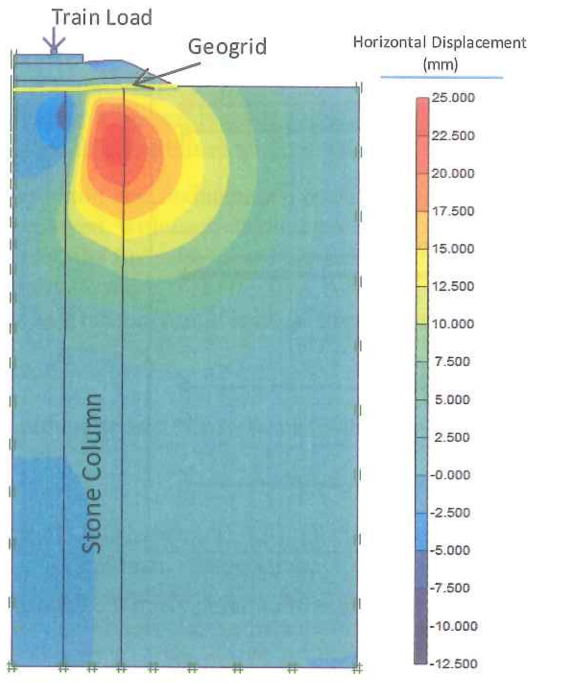

Figure 12: Profile of horizontal displacement under train loading for the ground improved using two stone columns offset 1.4 m from centre with one layer geogrid

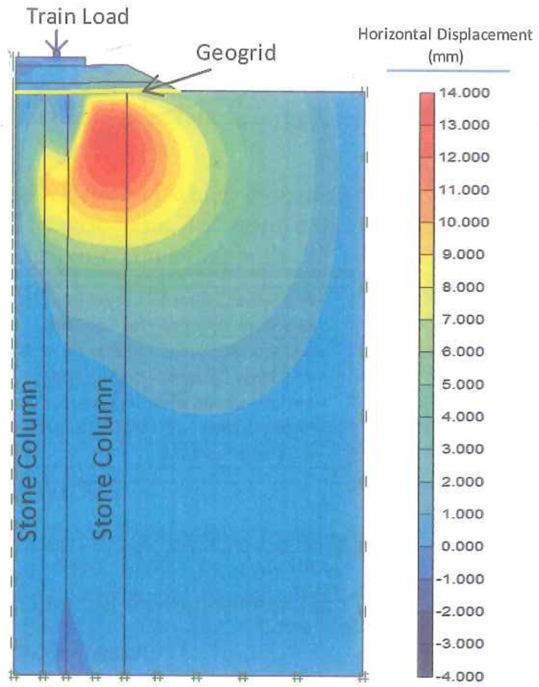

Figure 13: Profile of horizontal displacement under train loading for the ground improved using three stone columns offset 1.4 mm from centre with one layer geogrid

As expected, the maximum horizontal displacement of the sub-grade reduces when the number of improved columns increases from two to three in the cross section, due to higher level of improvement (24.5 mm and 14 mm for two and three improved columns, respectively). However, by comparing Figures 11 and 12, it becomes evident that when the offset distance of the columns from the track centreline increases, the maximum horizontal displacement of the improved sub-grade also increases. This means that the minimum critical horizontal displacement will be achieved when the improved columns are constructed side by side below the track centreline.

Figures 14 and 15 show the results for vertical displacement of each configuration modelled. The results clearly indicate that the optimum column pattern will occur, when stone columns and DSM columns just overlap in the cross section and are located right in the centreline of the track.

It can also be observed that the use of 2 columns (without geogrids) becomes less effective in reducing vertical settlements than geogrids only (without an improved column), when distance of columns from the centre line exceeds 1 m. Furthermore, the use of 2 stone or DSM columns with geogrids has limited benefits over the use of just geogrids, when the distance of columns from the track centreline is greater than 1600 mm. Figures 14 and 15 also show that the use of configurations with 3 stone columns located more than 700 mm (without geogrids) or 1200 mm (with geogrids) from track centre is less effective than a configuration with 2 columns and geogrids overlapped in the track centreline. It should be noted that predicted results clearly show that adding one more layer of geogrid between ballast and sub-ballast (i.e. having two layers of geogrids as shown in Figure 7) has insignificant effect on settlement reduction over one layer of geogrids, located between sub-ballast and sub-grade. Thus to improve the track performance one layer of geogrids would be adequate. Although the numerical analysis results in this study recommends application of deep soil mixing and stone columns and optimum column pattern to improve the weak formation beneath rail tracks, follow up work by the authors will be on further verification of the results, using case studies.

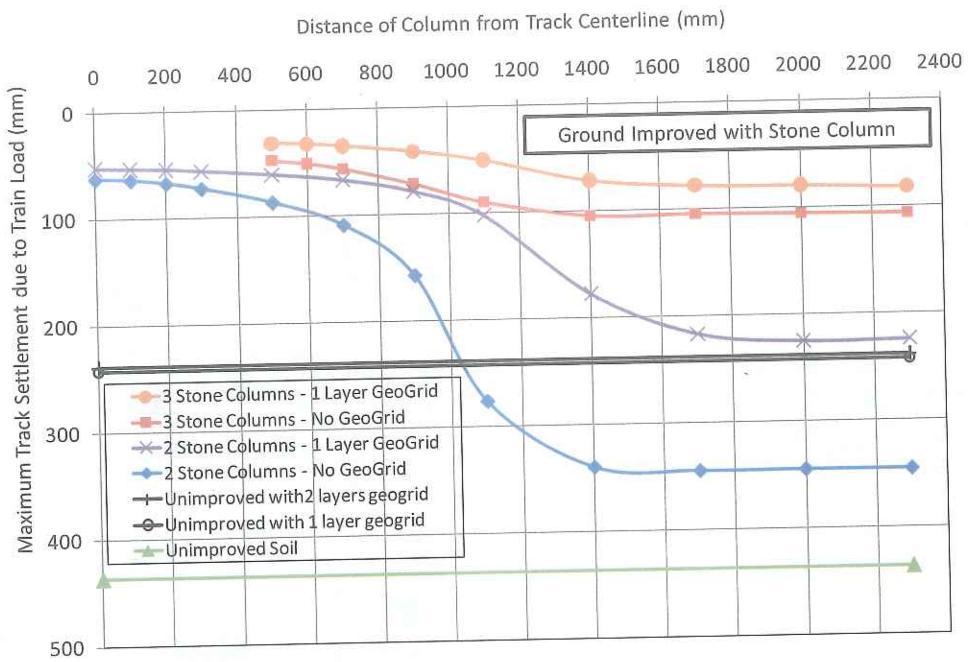

Figure 14: Variation of track settlement with the pattern of stone columns and distance of columns from the centreline.

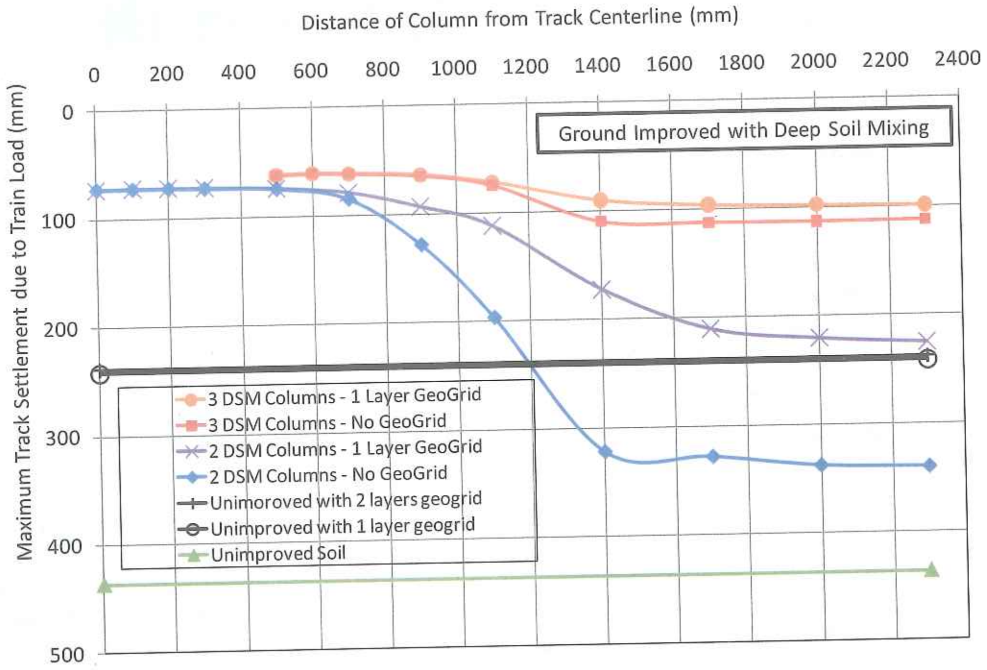

Figure 15: Variation of track settlement with the pattern of DSM columns and distance of columns from the centreline.

5 CONCLUSIONS

Millions of dollars is currently spent on maintenance of rail tracks in Australia and this will increase due to the construction of new rail lines and the increase in rolling stock traffic. It is important to keep the maintenance costs to a minimum possible level. The best way to achieve this goal is to focus on initial investment in building quality rail tracks, which will require less maintenance expenditure. This leads to a more sustainable rail system and a more viable mode of transport to handle the increasing population.

The findings of this research indicate that the cross-sectional configuration of stone or deep soil mixing columns has a profound impact on the level of soil improvement achieved. A greater number of columns spaced more closely together at the centre of the track give a larger level of settlement control, with the effectiveness of configurations with 2 columns making them uneconomical to implement, when located more than 1 m from the track centre. However, it has been observed that the use of 3 stone columns very close to the centre of the track (up to 500 mm) yields only a marginal soil improvement compared to configurations with 2 stone columns. The results also showed that when improved columns are combined with a single layer of geogrids, positioned between the sub-grade and sub-ballast, noticeable gains in settlement control can be achieved. The addition of another layer of geogrids, positioned between the sub-ballast and ballast layers, showed negligible improvement and hence, would not be considered economical for practical applications. In the case of configurations with 2 columns less than 300 mm from the track centre; the application of geogrids made them almost as effective as the optimum configurations with 3 stone columns (being 500 mm from the centreline) without geogrids.

Construction and maintenance costs play a significant role in the selection of which ground improvement technique to be employed, with each method needing to be assessed on a case by case basis. To improve the ground using semi-rigid columns, the use of a closely spaced configuration with 2 columns in conjunction with one layer of geogrids, would generally be more cost effective. Adopting a closely spaced configuration with 3 columns and geogrids is recommended when an extremely high level of improvement is required.

6 ACKNOWLEDGMENTS

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7 REFERENCES

Fatahi, B. & Khabbaz, H. (2011). "Enhancement of Ballasted Rail Track Performance Using Geosynthetics", The 2011 Geohunan International Conference, Hunan, China, June 2011 in Advances in Pile Foundations, Geosynthetics, Geoinvestigations, and Foundation Failure Analysis and Repairs (GSP 220) Proceedings of the 2011 GeoHunan International Conference, ed Adam F. Sevi; Jiyuan Liu; Cheng-wei Chen; Sao-Jeng Chao, ASCE, USA, pp. 222-230.

Fatahi, B., Khabbaz, H. and Ho, L.H. (2011), "Effects of geotextiles on drainage performance of ballasted rail tracks", Australian Geomechanics Journal, Vol. 46, No. 4, pp. 91-102.

Fatahi, B., Basack, S. Premananda, S. and Khabbaz, H. (2012). "Settlement Prediction and Back Analysis of Young's Modulus and Dilation Angle of Stone Columns", Australian Journal of Civil Engineering, Vol. 10, No. 1, pp. 67-80.

Fatahi B., Indraratna B. and Khabbaz H. (2007). "Soil Improvement Induced By Tree Root Suction", Australian Geomechanics Journal, Australian Geomecahnics Society, Sydney, Vol. 42, No. 4, pp.13-18.

Indraratna, B., Shahin, M.A. and Salim, W. (2007), "Stabilisation of granular media and formation soil using geosynthetics with special reference to railway engineering", J. Ground Improvement, Vol. 11(1): 27-43.

Indraratna, B., Salim, W. and Rujikiatkamjorn, C. (2011), "Advanced Rail Geotechnology – Ballasted Track", Taylor & Francis Group Publisher, United Kingdom.

Indraratna B. and Khabbaz, H. (2008). "Geotechnical Aspects of Ballasted Rail Tracks and Stabilising Underlying Soft Soil Formation". Proceedings of the International Conference on Advances in Transportation Geotechnics, Edited by Ed Ellis , Nick Thom , Hai-Sui Yu , Andrew Dawson , & Glenn McDowell, Uni of Nottingham, UK, 25-27 August: pp. 593-599.

Indraratna, B., Khabbaz, H. and Salim, W., (2006), "Geotechnical properties of ballast and the role of geosynthetics", Journal of Ground Improvement, ISSMGE, 10 (3), pp. 91-101.

Lieberenz, K. and Weisemann, U. (2002), "Geosynthetics in dynamically stressed earth structures of railway lines", Rail International, Schienen der Welt. Vol. 33, pp. 30-39. Suiker, A.S.J. (2002), "The Mechanical Behaviour of Ballasted Railway Tracks". Dissertation, Delft University of Technology, The Netherlands.

New South Wales Government (2010), *Metropolitan Transport Plan*, Sydney.

PLAXIS (2008), "User Manual of PLAXIS 2D", Version 9, Delft, The Netherlands

Raymond G.P. (1994), "Durability of Geotextiles in Railway Rehabilitation", Transportation Research Record, Washington, DC USA, Issue 1439: pp. 12-19

Rose, J. and H. Lees. Long-Term Assessment of Asphalt Trackbed Component Materials' Properties and Performance, Proceedings of the American Railway Engineering and Maintenance-of-Way Association 2008 Annual Conference, Salt Lake City, UT, September, 2008, 28p.

Selig, E. T. and Waters, J. M., (1994), "*Track Geotechnology and Substructure Management*", Thomas Telford Services, London, UK

Sydney Rail Performance Data (2011) "City Rail Information, Service Reliability", http://www.cityrail.info/about/our performance/service_reliability.jsp, (Accessed on 10/08/2011)

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Content Type	Academic / Scholarly
Format	Print
Website	http://australiangeomechanics.org/journal/
Description	News journal of Australian Geomechanics Society with news and technical papers in the general field of geomechanics.

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AUSTRALIAN GEOMECHANICS

Volume 48 No 3 | **Contents** | **September 2013**

Contents

[All papers have been refereed in accordance with the full DETYA review process, unless stated otherwise.]

[1] The authors have requested that this paper be published as a non-refereed technical paper.